Generic bio-economic modeling of plant diseases: an exploration

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Introduction

Cost-effective management of pests and diseases in plant production chains requires a thorough understanding of the system's dynamics and the effects of control measures. Existing analytical models of plant disease epidemics often do not match with managers' perception of the system (McRoberts et al., 2003; Madden, 2006) while simulation models generally have a case-specificity that limites the domain of application and does not enable generic insights (e.g., Thackray et al. 2004; Willocquet and Savary 2004; Breukers et al. 2006). Consequently, there is a need among plant health risk managers for generic tools that fit with their perception of the system and yet provide plausible results. To meet this need, we developed a generic bio-economic conceptual framework for plant disease epidemics and disease management. In this framework dynamical processes in the plant production chain are modeled from the perspective of a plant disease manager operating at the national level, i.e. a plant health authority such as the Dutch Phytosanitary Service.

The conceptual framework

The framework considers the true world as a collection of objects, structured in compartments. Objects represent (aggregations of) entities that can become infected or infested with the disease of interest. All objects of the same type are grouped in one compartment. Examples of compartments and corresponding objects are a production chain containing lot objects of a particular crop, arable land containing arable field objects, and woodland containing forest objects. Objects can multiply, die, and transmit disease within and between compartments via one or more pathways. Pathways may be partly or completely blocked by control measures. The likelihoods of birth, death, infection, and control differ periodically over time due to seasonality in crop production activities. This periodic variation is represented in the framework by splitting one time step (normally a year) in a series of periods, called phases. Figure 1 provides a diagrammatic representation of the system.

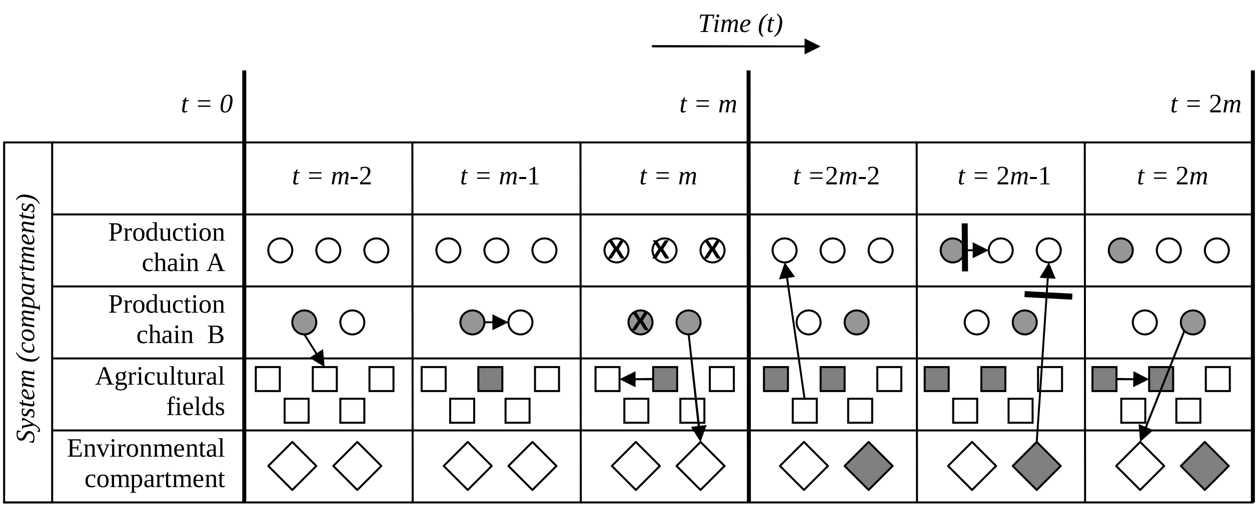

Figure 1. Schematic representation of modeled system according to the generic framework. Figures represent objects; shaded ones are infested. Arrows indicate transmission between objects; a bar indicates that transmission is blocked by a control measure. Objects with a cross are removed from the compartment.

The framework is structured according to the theory of periodic matrix modeling (Skellam 1966), where each phase has its own transition matrix. Adjustments and extensions to this structure were made to overcome some inherent limitations of matrix modeling. First, nonlinearity is introduced to account for the probability of multiple infection, which is a function of the fraction infested within a compartment. Second, memory is introduced to represent history effects of crop rotation on disease dynamics. Control measures are included as parameters that affect susceptibility of healthy objects (preventive measures), or transmission (reactive measures) and survival (eradication measures) of infested objects. An economic module quantifies the losses from crop damage and the direct costs of control measures. Indirect costs, such as impacts on trade and product prices, are not accounted for.

Results and discussion

The conceptual framework as described above was translated into a functional prototype model for three pathogens: *Ralstonia solanacearum*, a bacterium that causes brown rot of potatoes, *Phytophthora infestans*, an oomycete causing potato late blight, and *Meloidogyne chitwoodi*, a nematode causing damage to many root crops. Table 1 shows the compartments and types of objects defined for each of the three cases.

The three model applications comprise pathogens with very different biology, dispersal pathways, host sites, and potential control measures. Yet, simulation results for each pathogen were plausible based on expert judgment and agreement with empirical evidence, confirming that the framework is generic as well as valid for evaluating options for disease management at the production chain level. Important strengths of the modeling framework are thus genericity, plausibility in three case studies, and congruence with the level of decision making of plant health authorities that have a responsibility for mitigating economic impacts of plant disease at the national level.

The generic framework presented and tested in this paper provides a new analytical method for obtaining insight into dynamics and control of plant diseases. While its basic structure resembles a periodic matrix model, it deals with more complex systems for which the assumptions of matrix modeling (e.g. linearity in transition parameters, unrestricted population growth) do not hold. Also, it contains several unique features not captured by existing epidemiological models, and thus provides a valuable contribution to fundamental plant disease modeling.

Table 1. Overview of types of objects per case study. Each object type represents one compartment.

Compartment types	*R. solanacearum*	*P. infestans*	*M. chitwoodi*
production chains	• Seed potato lots • Ware potato lots	• Seed potato lots • Ware potato lots	• Seed potato lots • Ware potato lots • Flower bulb lots • Other root crop lots • Non-root crop lots
arable land	• Fields, not detected • Fields, detected	• Fields	• Fields, not detected • Fields, detected
environmental	• Surface water	• Waste piles	

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